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DEPRESSED SWEATING DURING EXERCISE AT ALTITUDE*

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Abstract—1. Acute exposure to moderate (552 Torr, 73.6 kPa) and high (428 Torr, 57.1 kPa) altitude resulted in a decrease in the thermosensitivity of arm, chest and thigh sweating during light and moderate exercise. This effect was not accompanied by any change in the esophageal temperature threshold for sweating onset at any of the three sites.

2. Whole body wettedness was decreased an average of 23% at high altitude during light (40% $\dot{V}O_2$ peak) and moderate (60% $\dot{V}O_2$ peak) exercise. There was no change in mean weighted skin temperature at either moderate or high altitude.

Key Word Index—Altitude; exercise; hypobaria; temperature regulation; sweating.

INTRODUCTION

The physical effect of a hypobaric environment on the control of sweating in humans has not been extensively studied. During acute exposure to simulated altitude (Greenleaf *et al.*, 1969), whole body sweating was elevated compared to sea level in men exercising at the same metabolic rate. In another study, which evaluated long term altitude exposure, the core temperature threshold for sweating onset was elevated compared to sea level (Raynaud *et al.*, 1980). An earlier evaluation from our laboratory (Kolka *et al.*, 1987), demonstrated the responsiveness (gain) of both local sweating and forearm cutaneous blood flow to increasing core temperature during exercise was suppressed by both moderate and high altitude in a temperate environment. Exposure to altitude is generally associated with a cool environmental temperature and the metabolic rate during exercise may be compromised by the level of hypoxia. Thus, bias may result in the experimental design of the study because exercise intensity may not be replicated between normobaria and hypobaria.

In the current study, we evaluated local sweating at three skin sites during exercise at sea level, moderate and high altitude. To further investigate the reported attentuation in sweating response seen during exercise at altitude, both a low and a moderate exercise intensity were evaluated in cool and temperate environments.

*The views, opinions, and or findings contained in this report are those of the authors and should not be construed as official Department of the Army position, policy or decision, unless so designated by other official documentation. Human subjects participated in these studies after giving their informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research. Approved for public release; distribution unlimited.

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METHODS

Eight healthy subjects volunteered to participate in the experiments following approval of all procedures by the institutional review board. The characteristics of the subjects are given in Table 1. Prior to environmental testing, subjects were oriented to all experimental procedures and performed peak aerobic power tests at a barometric pressure (P_B) of $P_B = 770$ Torr (102.7 kPa, sea level), $P_B = 552$ Torr (73.6 kPa, 8500 ft) and $P_B = 428$ Torr (57.1 kPa, 15,000 ft) in a random experimental order at 24 C; the subjects were not informed of the altitude during any test session. During each test, the subject was seated behind the pedals of a cycle ergometer, such that the legs were parallel to the floor during exercise. The peak aerobic power was evaluated during continuously increasing resistance (30 W each 2 min) and was determined by stability in oxygen uptake (< 150 ml) with an increase in ergometer resistance. The four female subjects were tested only during the early follicular phase of the menstrual cycle (Stephenson and Kolka, 1985).

Experiments were conducted between 0800 and 1200 h, with any one subject tested at the same time of day in all experiments to control for circadian variability in heat loss responses (Stephenson *et al.*, 1984). On the day of an experiment, the subject reported to the hypobaric chamber, was weighed and sat in the chair of the cycle ergometer. The ambient temperature of the chamber was set to either 20 or 30 C with an ambient water vapor pressure of 1.2 kPa. The subject swallowed a catheter containing a small thermocouple for the measurement of esophageal (T_{es}) temperature (based on 25% of the subject's height adjusted for the highest thermal reading). Each subject drank approx. 200 ml of water during this procedure. Eight surface copper–constantan thermocouples were attached to the forehead, chest, back, upper arm, forearm, hand, thigh and calf for the calculation of a mean weighted skin ($\bar{T}_{sk}$)

Table 1. Physical characteristics of the subjects

	Sex	Age (yr)	SA_2 (m^2)	Wt (kg)	$\dot{V}O_2$ peak ($l\ min^{-1}$) 770 Torr	552 Torr	428 Torr
1	M	24	1.77	69.8	3.76	3.57	2.80
2	M	33	1.99	80.0	2.77	2.68	2.77
3	M	25	1.87	73.9	2.49	2.58	2.21
4	M	27	1.89	73.6	4.06	3.37	2.85
5	F	19	1.68	64.7	2.60	2.25	1.90
6	F	24	1.65	60.9	2.20	1.87	1.59
7	F	25	1.95	82.5	2.83	2.72	2.57
8	F	29	1.73	63.0	2.61	2.37	2.22
Mean		25.8	1.82	71.1	2.92	2.68	2.36
SD		4.1	0.13	7.9	0.65	0.56	0.46

temperature (Nishi and Gagge, 1970). Small dew-point sensors were attached to the chest, arm and thigh to measure local sweating rates from these areas. These sensors were ventilated with air from the chamber (500 ml·min^{-1}) and flow rates were calibrated *in situ* at the end of each experiment. Sweating rates were calculated as described previously (Graichen *et al.*, 1982; Kolka *et al.*, 1987). T_{es}, $\bar{T}_{sk}$, and $\dot{m}_s$ from all three sites were measured continuously during exercise. Heart rate from three chest leads was measured each 5 min during exercise. Skin wettedness (Gagge, 1972; Gonzalez *et al.*, 1985) was calculated as the ratio of evaporative heat loss from the skin (E_{sk}) to maximal evaporative power of the environment (E_{max}) as:

$$w = (\lambda \cdot 60) \cdot A_D\ h_e(P_{s,sk} - P_a)\ (\%)$$

where the first half of the equation transfers sweating rate in $g \cdot min^{-1}$ by the product of the latent heat constant ($\lambda = 0.68\ W \cdot h/g$)·min/DuBois surface area, and in the second half of the equation, h_e is the evaporative heat transfer coefficient, $P_{s,sk}$ is the saturated water vapor pressure at $\bar{T}_{sk}$ and P_a is the ambient water vapor pressure.

The subject equilibrated to the environmental temperature and then the appropriate environment was simulated by decompression. The subject exercised at either 40 or 60% of the previously determined altitude-specific $\dot{V}O_2$ peak for a period of 35 min. Each subject was tested on nine separate occasions as shown in Table 2. All combinations of exercise intensity, ambient temperature and altitude were counterbalanced. Metabolic rate was calculated from oxygen uptake measurements before exercise and frequently during the exercise bout.

The T_{es} threshold for sweating was analyzed for each experiment by analyzing the inflection point of the exercise transient for changes in sweating to T_{es} increase. The exercise transient phase was that point in exercise where a rapid increase in sweating and T_{es} occurred. A regression equation was then calculated for each of the three sweating sites for each of the 72 experiments. The T_{es} threshold for sweating was calculated where $\dot{m}_s$ exceeded 0.06 mg·cm^{-2}·min^{-1}. Exercise at 40% $\dot{V}_{O_2}$ peak and 20 C caused little sweating and the analysis of $\dot{m}_s$ to T_{es} could not be ascertained for all subjects. Therefore only data from the thermal steady-state during exercise are reported for these experiments. An analysis of variance with repeated measures (altitude by exercise intensity by temperature) was used where appropriate. Data in the Results are presented as mean ± standard deviation with significant differences at $P < 0.05$.

RESULTS

Low intensity exercise at 20 C was an insufficient stimulus to consistently increase heat production enough to evaluate responses of sweating at sea level or either of the altitudes. The subjects had sufficient heat exchange from the skin to the air, such that the low heat production from the exercise was readily dissipated. The average whole body sweating rates during these experiments was slightly less than 4 $g \cdot min^{-1}$. The data during 22–30 min of exercise for these experiments are presented in Table 3 along with that from the other two exercise-temperature combinations.

Resting esophageal temperature was relatively stable during the nine experiments due partly to strict adherence to circadian timing for individual experiments. However, at 428 Torr (57.1 kPa) there was a decrease in resting T_{es} which averaged 0.12 C ($P < 0.05$) compared to sea level experiments.

The average relative exercise intensity at which the subjects exercised was 37 ± 3% for light exercise and 55 ± 3% for moderate exercise at all three altitudes and both ambient temperatures. These relative intensities resulted in a 0.34 C increase in T_{es} during light exercise and 0.58 C increase in T_{es} during moderate exercise.

The mean weighted skin temperature was unchanged by altitude, but was, as shown repeatedly, related to ambient temperature (Gagge, 1972). Mean

Table 2. Experimental design of the study. Each subject participated in one experiment in each of the nine conditions presented. Each experiment consisted of an equilibration period (rest) and 35 min of seated cycle exercise at the requisite temperature and exercise intensity

	Sea level	2593 m (552 Torr)	4575 m (428 Torr)
20 C	40% $\dot{V}O_2$ peak	40% $\dot{V}O_2$ peak	40% $\dot{V}O_2$ peak
20 C	60% $\dot{V}O_2$ peak	60% $\dot{V}O_2$ peak	60% $\dot{V}O_2$ peak
30 C	40% $\dot{V}O_2$ peak	40% $\dot{V}O_2$ peak	40% $\dot{V}O_2$ peak

Table 3. Mean ± SD data collected during exercise (22–30 min) at sea level, moderate and high altitude on 8 subjects during light (40% $\dot{V}O_2$ peak) and moderate (60% $\dot{V}O_2$ peak) exercise at both 20 and 30 C

	Sea level			552 Torr			428 Torr		
	60/20	40/30	40/20	60/20	40/30	40/20	60/20	40/30	40/20
T_{es}	37.11	36.93	36.93	37.19	37.00	36.96	37.13	36.98	36.77*
	(0.17)	(0.13)	(0.31)	(0.20)	(0.23)	(0.26)	(0.16)	(0.20)	(0.35)
$\bar{T}_{sk}$	31.02	34.42†	31.04	31.41	34.48†	31.26	31.69	34.59†	31.53
	(0.77)	(0.35)	(0.77)	(0.75)	(0.38)	(0.52)	(0.39)	(0.76)	(0.48)
ΔT_{es}	0.50	0.33	0.33	0.54	0.39	0.29	0.70	0.43	0.29
$\dot{V}O_2$	1.55	0.98	1.03	1.42	0.95	0.99	1.39	1.02	0.92
	(0.30)	(0.17)	(0.13)	(0.29)	(0.17)	(0.19)	(0.33)	(0.19)	(0.17)
$\dot{M}_{sw}$, g·min^{-1}	8.0	8.1	3.7‡	8.0	6.1	3.7‡	6.2	7.1	4.0‡
	(3.4)	(4.0)	(1.1)	(1.4)	(1.8)	(1.0)	(1.7)	(2.5)	(2.0)
T_{es}, rest	36.61	36.63	36.60	36.65	36.61	36.67	36.44*	36.55	36.48*
	(0.20)	(0.16)	(0.19)	(0.24)	(0.22)	(0.29)	(0.23)	(0.15)	(0.23)

*Different from sea level, $P < 0.05$.
†Different from 20 C, $P < 0.05$.
‡Different from 60%, 20 C and 40%, 30 C, $P < 0.05$.

skin temperature averaged 34.5 C during exercise at 30 and 31.3 C during exercise at 20°C. Whole body sweating calculated from the change in body weight during an experiment was higher during moderate exercise in the cool environment and light exercise in the warm environment than light exercise in the cool environment.

Whole body wettedness calculated from the observed evaporative heat loss divided by the maximal evaporative power of the environment (corrected for altitude) decreased 5 and 34% at 552 Torr (73.6 kPa) and 428 Torr (57.1 kPa), respectively during light exercise in the cool environment. During light exercise at 30 C, skin wettedness (w) was decreased 16 and 25% at 552 Torr (73.6 kPa) and 428 Torr (57.1 kPa). Finally, w was decreased by 3 and 28% during moderate exercise at 20 C at 552 and 428 Torr (73.6 and 57.1 kPa), respectively.

The analysis from the individual regression equations for arm, chest and thigh sweating during increasing T_{es} for the 8 subjects during exercise at three altitudes is given in Table 4. The T_{es} threshold for the onset of sweating was unchanged by altitude for any of the three sites measured. There were differences, however, in the T_{es} threshold from site to site, independent of altitude. A general suppression in thermosensitivity (gain) for sweating was apparent during acute altitude exposure, with no significant difference between the two altitudes. The thermosensitivity of chest sweating was significantly reduced 36% ($P < 0.05$) during moderate exercise at 552 Torr (73.6 kPa). A similar suppression was observed during light exercise at moderate altitude. The thermosensitivity of arm sweating was reduced 42% during both moderate and light exercise at 552 Torr (73.6 kPa). The gain of thigh sweating was decreased 23 and 29% during moderate and light exercise at 552 Torr (73.6 kPa).

DISCUSSION

We evaluated sweating to changing esophageal temperature from three skin locations during acute exposure to simulated moderate or high altitude. The exercise intensity was adjusted at each altitude relative to the peak oxygen uptake measured at that specific altitude. Consequently, the change in esophageal temperature during exercise at a given intensity was similar at sea level, moderate and high altitude, thereby controlling heat production and

Table 4. Mean (±SD) esophageal temperature for the onset of sweating (T_{es}) and thermosensitivity ($\dot{m}_s$ T_{es}) for the 8 subjects during light and moderate exercise at three altitudes

	Sea level	552 Torr	428 Torr
60%, 20 C			
Chest			
T_{es}, C	36.52 (0.45)	36.49 (0.33)	36.44 (0.25)
$\dot{m}_s$ T_{es}	1.04 (0.40)	0.67 (0.27)*	0.60 (0.20)*
Arm			
T_{es}, C	36.62 (0.30)	36.61 (0.37)	36.51 (0.27)
$\dot{m}_s$ T_{es}	1.84 (0.67)	1.07 (0.63)*	0.90 (0.11)*
Thigh			
T_{es}, C	36.56 (0.38)	36.42 (0.31)	36.27 (0.25)
$\dot{m}_s$ T_{es}	1.31 (0.41)	1.01 (0.21)*	0.95 (0.31)*
40%, 30 C			
Chest			
T_{es}, C	36.46 (0.28)	36.62 (0.22)	36.53 (0.20)
$\dot{m}_s$ T_{es}	1.27 (0.69)	0.82 (0.42)*	0.67 (0.29)*
Arm			
T_{es}, C	36.57 (0.23)	36.81 (0.20)	36.70 (0.14)
$\dot{m}_s$ T_{es}	1.48 (1.21)	0.86 (0.49)*	0.96 (0.42)*
Thigh			
T_{es}, C	36.41 (0.16)	36.54 (0.22)	36.49 (0.24)
$\dot{m}_s$ T_{es}	2.01 (1.25)	1.43 (0.34)*	0.93 (0.26)*

*Different from sea level $P < 0.05$.

allowing comparisons of sweating responses at the different altitudes.

The general suppression in the thermosensitivity of sweating during the exercise transient seen in the present study is consistent with changing peripheral input to the sweat gland. In our previous paper (Kolka *et al.*, 1987), we suggested that local skin influences, such as hydration status, skin temperature or heat transfer characteristics may contribute to the suppression of sweating thermosensitivity. However, mean and local skin temperatures were not significantly affected by acute altitude exposure in the present study. We cannot directly address changes occurring at or just below the skin surface, except to recognize that whole body skin wettedness was reduced at both moderate and high altitude owing to the increased evaporative heat transfer coefficient observed with the reduced barometric pressure (Cena *et al.*, 1982; Gonzalez and Cena, 1985).

The consistent increase in body temperature during a specific exercise intensity which occurred at all altitudes allowed an evaluation of whole body sweating with a matched internal thermal drive, thus no effect was apparent in contrast to an earlier report (Greenleaf *et al.*, 1969). In that earlier study, subjects exercised at 46% $\dot{V}O_2$ peak at sea level contrasted with 66% $\dot{V}O_2$ peak at 4000 m. The average increase in esophageal temperature from rest to exercise was 1.13 C at sea level and 1.37 C at 4000 m, associated with significantly increased sweating rate (16%). During acute altitude exposure, the mass transfer coefficient is increased thereby increasing evaporative heat loss for a given volume of fluid secreted by the sweat glands (Cena *et al.*, 1982; Gonzalez and Cena, 1985). Similarly, dry heat exchange is augmented due to the decrease in air density allowing more free transfer of molecules from the body surface to the air. These physical properties of the hypobaric environment resulted in less requirement for regulatory sweating to achieve thermal equilibrium during exercise in the simulated hypobaric environments.

The responses of the 4 female subjects were not different from those of the 4 male subjects. All individuals were habitual exercisers and by controlling exercise intensity, time of day and menstrual cycle phase, it was possible to evaluate the genders simultaneously and show similar responses with regard to the control of sweating.

Similar responses to acute exposure to hypobaria were observed from all three different skin site evaluated in the present study independent of exercis intensity or ambient temperature. It was apparent that differences existed in thermosensitivity and T_{es} threshold for the various sites measured, but this is not a new or unexpected finding (Bullard *et al.*, 1967; Bullard *et al.*, 1970; Nadel *et al.*, 1971). In general, the threshold for sweating onset from the chest and thigh occurred at a lower esophageal temperature than the forearm in the present study. Whatever the pattern of onset, it was consistent within a subject at sea level, 552 Torr (73.6 kPa) and 428 Torr (57.1 kPa). The thermosensitivity was variable from site to site and from subject to subject. As previously suggested (Nadel *et al.*, 1971), the density of sweat glands in the area and the individual innervation or recruitment pattern of those glands in each area combined with individual responses to central and peripheral thermal stimuli may be variable from subject to subject. The key observation from the present study was the consistent suppression in sweating thermosensitivity at all skin sites measured with acute hypobaric exposure.

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